PRECISION WEED MANAGEMENT TECHNIQUES FOR SMART AGRICULTURE

Abstract

The global population's growth has led to an increased demand for food production, consequently placing greater pressure on agricultural systems. Additionally, challenges linked to climate change, water scarcity, and diminishing arable land pose significant threats to the sustainability of farming. Weeds play a detrimental role in agricultural systems by competing for natural resources, thereby reducing both the quality and productivity of food production. To address this issue effectively and sustainably, it is essential to integrate various weed management methods, such as cultural, mechanical, and chemical approaches, in a balanced manner that does not harm the overall agrarian ecosystem. Consequently, it is crucial to avoid overreliance on intensive mechanization and herbicide usage, as the development of herbicide-resistant weed biotypes has become a substantial global concern, dating back to the emergence of 2,4-D resistance in the United Kingdom, Hawaii, the USA, and Canada in 1957. Given this situation, weed scientists must explore alternative weed management strategies that enhance agricultural productivity within the context of smart agriculture. Simultaneously, recent advancements in weed control technologies have the potential to increase food production levels, reduce input requirements, and mitigate environmental damage, thus moving us closer to more sustainable agricultural systems. Precision weed management (PWM) is one such alternative strategy that increases farm productivity by combining integrated weed management practices (chemical, mechanical, manual, and cultural) with

Authors

Gayatree Mishra
Assistant Professor
Department of Agronomy
Faculty of Agricultural Sciences
Siksha 'O' Anusandhan (Deemed to be University)
Bhubaneswar, India.

Ashok Kumar Mohapatra
Professor
Department of Agronomy
Faculty of Agricultural Sciences,
Siksha 'O' Anusandhan
(Deemed to be University)
Bhubaneswar, India
ashokmohapatra1957@gmail.com

Sweta Rath
Assistant Professor
Department of Agronomy
Faculty of Agricultural Sciences
Siksha 'O' Anusandhan
(Deemed to be University)
Bhubaneswar, India.

site-specific, economically viable weed sensing systems (both aerial and ground-based). In order to help the farming community, weed experts should proactively focus their future research efforts on developing and integrating these techniques.

Keywords: Integrated weed management, Precision weed management, Sustainability, agricultural production.

I. INTRODUCTION

Weeds have existed since the dawn of civilization and are unlikely to vanish in the foreseeable future. It is widely recognized that weeds consistently and universally present a significant threat to agricultural productivity (Buhler et al., 2000). Weeds represent a substantial obstacle to global agricultural output. By 2050, there will be nine billion people on the planet, up from the current seven billion (Young, 2014). The needs of the growing population cannot be met by the current levels of agricultural production, and meeting this anticipated need could prove to be a huge challenge for civilization. Factors such as climate change, the depletion of arable land and water supplies, and the ongoing threat posed by weeds, pests, and diseases increase the strain on agricultural systems to an unprecedented degree. These issues affect sustainability, the health of our planet, and the standard of living for all living things in the short and long terms. An ongoing problem in agriculture since the beginning has been weeds. They impede crop growth by competing with plants for essential resources such as water, nutrients, and sunlight, resulting in significant crop production losses. Typically, weeds are managed either through mechanical methods involving specific cultivation practices or by employing herbicides. Nevertheless, the extensive use of mechanization leads to soil erosion, which depletes soil fertility. Herbicide usage introduces contamination into soil, water, food, and the air, leading to health issues in both humans and animals (Ribas, 2009). This situation gives rise to herbicide resistance and disrupts ecosystems. From this perspective, biodiversity plays a pivotal role in providing ecosystem services within agricultural systems.

Agrobiodiversity can directly impact various services, such as increasing food resources through enhanced crop diversity or improving water quality and reducing runoff by diversifying cover crops. However, the preservation of agrobiodiversity and the services it provides, including pollination, enhanced soil structure, and natural pest control, is facing growing threats due to the extensive eradication of weeds and wild plants and the potential toxicity of agrochemical inputs (Anonymous, 2017).

According to MacLaren et al. (2020), weeds maintain biodiversity and soil quality among other ecosystem activities that are essential to the long-term sustainability of agroecosystem productivity. Therefore, switching to sustainable weed control is essential for a number of environmental, social, and economic reasons, including its ability to preserve natural resources for the future and provide more affordable farms (Monterio and Santosh, 2022).

Agricultural 4.0, a fourth revolution in agriculture that incorporates Information and Communications Technologies (ICT) with conventional agricultural methods, has been taking place in the last few years (Sundmaeker et al., 2020). In order to increase crop yields, lower costs, and optimize resource inputs, smart farming makes it possible to monitor a variety of agricultural parameters, including environmental conditions, crop growth status, soil conditions, irrigation, pest and fertilizer management, weed control, and greenhouse production environments. Significantly, smart farming lessens the environmental impact of traditional farming methods by using green technologies (Nukala et al., 2016).

Sustainable weed management encompasses a range of options for controlling weeds, with one key approach being integrated weed management (IWM). IWM involves the strategic application of multiple weed control methods and strategies to optimize crop production and increase profitability for growers. According to Hartzler and Buhler (2007), this strategy is predicated on scientific information, effective management techniques, proactive measures, frequent monitoring, and effective control procedures.

Current weed management methods frequently lack the accuracy needed to safely and effectively manage weeds without having unfavorable side effects. For farmers, controlling weeds is the biggest productivity expense in many areas. Many producers' options in conventional systems have been constrained by issues like herbicide resistance and the unintentional spread of administered herbicides. Additionally, while biotech crops are an option, concerns about their long-term biosafety have emerged as a significant limitation to their continued development (Rao, 2018).

In this context, a broad and swiftly advancing array of novel technologies have been devised and put into action within agricultural practices. Additionally, these technologies are essential for developing environmentally and economically sustainable weed control methods. Specifically, precision weed management reduces resource inputs without sacrificing the effectiveness of weed control. Numerous opportunities for cost reductions and technological breakthroughs in the fields of sensing, weeding, and spraying technologies have been shown by research and experimentation. Some of these innovations have already found commercial use, which is noteworthy (Christensen et al., 2009).1.2 Drawbacks of Conventional and Non-Conventional Method of Weed Control.

In addition to the benefits associated with herbicide use in weed control, there are also drawbacks, primarily stemming from the limitations of conventional spraying methods. Prolonged utilization of the same category of herbicides on the same parcel of land can disrupt ecological equilibrium by causing shifts in weed populations, fostering herbicide resistance among weeds, and contributing to environmental contamination (Gnanavel, 2015). Herbicide-resistant weed populations can actually arise as a result of over-reliance on herbicides with similar mechanisms of action. As a result, a few difficult-to-manage weed species frequently take over agricultural landscapes, failing to adequately maintain farmland biodiversity (Rueda-Ayala et al., 2020). For example, Oenothera laciniata, the cutleaf evening primrose, has become resistant to both paraquat and glyphosate (Sims et al., 2018). Crops designed to withstand herbicides that were previously non-selective have been developed in response to the emergence of weed resistance to these treatments. Globally, biotech transgenic crops were grown on over 190 million hectares of land as of 2019; of these, almost 80% of the land was planted with herbicide-resistant cultivars, either alone or in conjunction with insect resistance (ISAAA, 2019). Herbicide-resistant (HR) biotech crops have improved agricultural output worldwide and farmers' incomes (Beckie et al., 2019), despite justifiable worries about consumer biosafety.

Herbicides can also result in adverse consequences, including the contamination of both surface and groundwater, along with the presence of herbicide residues within the food chain (Lancaster, 2021). Furthermore, chemical herbicides may cause a major decline in earthworm and soil microbial populations, and the long-term effects of weed control may include a reduction in soil biodiversity and nutrient availability (Mia et al., 2020).

The biological diversity, soil structure, and water retention capacity of soil are only a few of the factors that are severely harmed by excessive tillage techniques. Tillage reduces the amount of carbon and nitrogen that microbes may access. The sustainability of crop production and ecosystem services are threatened by the intrinsic soil erosion and degradation linked to tillage-based systems, which intensify environmental contamination from agricultural chemical inputs like pesticides and fertilizers. This poses a long-term threat to global food security. Furthermore, adverse weather conditions can pose limitations to tillage operations. Minimum tillage or non-tillage approaches also carry potential issues. They may aggravate the phytosanitary conditions by increasing the likelihood of fungal infections and weed infestations in crops, as well as increasing bulk density and soil compaction in the topsoil (Peera et al., 2020). In addition, farmers who choose to use less tillage might use more pesticides and herbicides to counter these dangers, which would increase the levels of phytotoxicity in the soil (Monterio and Santosh, 2022).

For the purpose of controlling weeds, ground cover techniques, burning, or livestock grazing have certain drawbacks as well. For example, applying mulching on a wide scale can be expensive and may change the qualities of the soil because the same mulching material is being used repeatedly. Moreover, crops may experience allelopathic impacts from specific organic mulches (Peera et al., 2020). Furthermore, seeds found in a variety of organic mulch varieties, including grass and straw, may promote the growth of weeds and worsen soil acidity. When cover crops are used, costs associated with purchasing specialized equipment, overseeing more complex farming techniques, and allocating time to planting and harvesting cover crops rather than cash crops must be considered. Because living mulches increase the danger of illnesses, increase pest populations, and compete for nutrients and water, they may impede the growth and productivity of primary crops. Furthermore, allelopathy may be facilitated by living mulches (Dabney et al., 2001). In order to solarize soil, temperatures must be raised to levels that can be fatal to fungi and bacteria. Some species can break dormancy if the fatal temperature is not reached, which leads to the appearance of a new wave of weed seedlings, which typically appear in the topsoil layer (Sims et al., 2018). After solarization, a surge in nutrient availability typically occurs, which needs to be managed by promptly planting crops after removing the plastic cover to prevent nutrient loss. Flaming as a weed control strategy can consume significant amounts of fuel and water, and there are restrictions on its summer use due to fire prevention concerns. However, the availability of smaller, more portable units offers an additional tool for targeted weed control, particularly around areas like sheds and other infrastructure (Pannacci et al., 2017). Lastly, weed control through livestock grazing has the potential to harm soil structure and non-target species, facilitate the dissemination of weed seeds through animal feces or on their wool, hair, or hooves, and even lead to a decline in animal condition or weight (Popay and Field, 1996).

Several of the constraints mentioned previously can be alleviated or entirely resolved through the integration of precision weed management technologies. Leveraging the internet, various sensor types, artificial intelligence, or machine learning offers promising enhancements to integrated weed management (IWM). It could be argued that we are embarking on a new phase in agriculture, often referred to as Agriculture 4.0, where precision becomes the standard practice (Santos and Kienzle, 2020).

II. ADVANCED TECHNIQUES FOR WEED MANAGEMENT

Throughout history, farmers have consistently regarded weed management as a central aspect of agricultural practice. Controlling weeds represents a significant and often intricate challenge in agriculture, presenting a complex and sometimes contentious problem to address. From a practical standpoint, weed control accounts for around one-third of the total costs related to field crop production (Gnanavel, 2015). This farming method goes beyond only controlling current weed problems; instead, it emphasizes stopping weed propagation, lowering weed emergence after crop planting, and lessening weed competition with the crop (Monterio and Santosh, 2022).

Today, weed control in agricultural systems has developed into two main paths, each with its own methodology. On the one hand, synthetic herbicides are widely used, while mechanical, cultural, and physical approaches are the main means of controlling weeds (Scavo and Mauromicale, 2020). But mechanical approaches are frequently seen to be ineffective, and pesticide use has been linked to detrimental effects on ecosystems. The disadvantages that both mechanical and chemical weed control techniques have as a result will probably make them less effective in weed management projects down the road. As a result, a thorough weed management strategy that reduces the drawbacks of chemical and mechanical weed control methods is crucial (Sims et al., 2018). In fact, a new paradigm for managing weeds in contemporary agriculture is desperately needed, one based on ecological principles and non-traditional weed control techniques. Achieving sustainable weed control for crops can have a big influence on how machinery operates, lessen the habitats of pests like voles, and boost the economy by improving the quality of harvested goods to meet market demands (Hammermeister, 2016).

In sophisticated agricultural systems, integrated weed management (IWM) is essential for controlling weeds, especially in industrialized nations like the European Union. However, its uptake in underdeveloped countries is still relatively low. Integrated Weed Management (IWM) stresses the employment of many weed management methods—such as agronomic, physical, mechanical, and chemical approaches—in a system rather than depending only on one technique. This strategy is important for reducing the selection pressure that can cause resistance to emerge to any one weed management technique (Chauhan, 2020).

Moreover, the utilization of non-chemical weed tactics becomes essential in minor crops where chemical compounds are scarce. In contrast to traditional practices, IWM integrates numerous agroecological principles. This includes understanding the impact of conservation tillage and crop rotation on weed seed bank dynamics, the ability to forecast the critical period when weed interference competes with crops, and identifying the specific critical levels of crop or weed interactions (Sims et al., 2018).

Moreover, current weed management techniques are not precise enough to manage weeds safely, effectively, or without unfavorable side effects. Weed control is considered by farmers to be their main production expense in many areas. There aren't many options available for producers in conventional systems due to herbicide resistance developing and unintentional herbicide movement. The size of farm holdings and related expenses determine how successful ground- and aerial-based remote sensing systems are, so larger land holdings are a better fit for this technology. Therefore, it is unlikely that precision weed management

(PWM), despite its great promise, will be commercially successful in India very soon. Currently, over 85% of India's farm holdings are smaller than two hectares; by 2030, that percentage is expected to rise to 91%. Small holdings, however, only make about 45% of all the land that is farmed.

Excessive dependence on a single weed management approach can gradually diminish its effectiveness in controlling weeds, as previously discussed with the development of resistance due to the continuous use of the same herbicide. Consequently, implementing need-specific integrated weed management (IWM) is a more successful course of action. IWM is based on the diversification principle and includes a variety of tactics that go beyond the use of herbicides. These tactics include post-harvest, pre-planting, and post-harvest handling techniques. When formulating an IWM plan, two critical factors come into play: a) the specific weed species being targeted and b) the time, resources, and capabilities required for its successful implementation.

In the larger framework of Integrated Weed Management (IWM), emerging technologies hold the capacity to revolutionize the way that weed control is currently done. While preserving the efficacy of weed control, they present the possibility of greatly lowering environmental consequences such drift, herbicide resistance, and the high costs of labor and inputs. Various methods are under development for the observation and detection of weeds, enabling the precise application of control measures whenever and wherever needed. This shift in perspective relies on interdisciplinary collaboration to harness the capabilities of advanced technology tools for weed management (Young, 2014). In the following section, we will explore the contributions of Precision Weed Management to weed control, representing a substantial advancement within the realm of IWM (Monterio and Santosh, 2022).

III. PRECISION WEED MANAGEMENT

Uniform application of weed management inputs throughout the field is a frequent practice in crop, soil, and pest management techniques. However, for a variety of reasons related to agro-ecological parameters, the distribution and intensity of weed infestations do not always cover the field; rather, they typically display an uneven, patchy pattern. As a result, sprinkling herbicides evenly over a field in which the target weeds are not dispersed equally may waste resources, which raises issues with the economy, the environment, and the social elements of herbicide use. Herbicide usage was reduced by 60% and 92% for dicot and monocot weeds, respectively, in spring barley cultivation and by 11% and 81% for the same weed categories in maize, according to Gerhards et al. (2002). Typically, the actual requirement for herbicide application falls within a range of 7% to 64% of the total area, indicating potential herbicide savings. The inherent variability in weed distribution and the prospect of minimizing herbicide quantities have spurred numerous weed scientists to explore improved weed management practices, including the adoption of precision weed management (Rao, 2021).

With the following benefits, precision weed management (PWM) offers a powerful toolkit to increase the efficiency of weed control:

- Reduces herbicide expenses and environmental concerns, while enhancing weed control effectiveness, ultimately fostering increased acceptance of herbicide utilization.
- Facilitates the application of the precise amount of management inputs to target weeds at the appropriate timing.
- Minimizes the wasteful utilization of inputs, contributing to environmental improvements.
- Delays, and in some cases, potentially prevents the emergence of herbicide-resistant weed species.
- Mitigates the buildup of herbicide residues in the soil, water, and the broader environment.
- Has the potential to decrease or circumvent herbicide toxicity to crops.

Numerous Precision Weed Management (PWM) techniques are under development to identify and locate weeds, enabling the targeted application of control measures precisely when and where they are required. Among these strategies, site-specific weed control and robotic technology stand out as two noteworthy techniques. Beyond chemical treatments, these strategies cover a variety of different ways.

IV. SITE-SPECIFIC WEED MANAGEMENT

The strategy known as "site-specific weed management" (SSWM) entails using machinery or equipment fitted with cutting-edge technology that can detect weeds growing next to crops and maximize targeted elimination of those weeds (Brown and Noble, 2005; Christensen et al., 2009). This strategy is based on the idea that the degree of management methods should be adjusted to the true amount of weed infestation, with treatment concentrated only in regions where weed density exceeds a predefined threshold level that requires intervention (Hamouz et al., 2013). It is feasible to drastically cut pesticide consumption by 40–60% by applying the necessary amounts of herbicides when weed density hits the point at which weed competition is likely to impair crop development. Different selective herbicides are used, singly or in combination, to control grass and broad-leaf weeds in specific weed-infested areas. Precise threshold level setting is essential for SSWM effectiveness and dependability to produce the best results.

Three essential components are necessary for SSWM technologies to succeed (Christensen et al., 2009):

- A system for detecting, localizing, and quantifying the characteristics of weeds and crops.
- A weed management model that optimizes treatments based on weed species density and composition by leveraging data and insights on crop-weed competition, population dynamics, the biological efficacy of control methods, and decision-making algorithms.
- A precision weed control apparatus, featuring a sprayer equipped with individual

controllable boom segments or an array of nozzles, facilitating the targeted application of herbicides with spatial variability.

A vital component of SSWM technology is the varied agro-ecosystem, which consists of individual weed and crop plants. Individual plants, groups or patches of plants within a field, or even an entire field, can all be considered these things. In terms of weed control, Christensen et al. (2009) organized the geographical resolution on a farm into four hierarchical levels:

- Apply treatment to individual plants with the use of precision spraying nozzles, adjustable mechanical devices, or laser beams, ensuring high accuracy.
- Application tailored to a grid corresponding to the resolution, such as adjusting the spray through a nozzle or a hoe unit.
- Address weeds patches or subfields containing groups of weed plants.
- Treat the whole field uniformly.

V. WEED SENSING SYSTEMS

There are two types of weed-sensing systems: aerial-based and ground-based, according to Wang et al (2019). Digital cameras or non-imaging sensors are used in these systems. In larger regions, remote sensing—using planes or satellites to provide farms with maps of weed presence—is the most cost-effective method, as shown by David and Brown (2001) and Fernández-Quintanilla et al. (2018).

1. **Ground-Based Sensing System:** This method uses a mobile platform with a sprayer and multi-spectral image sensors, like color digital optical cameras. According to Christensen et al. (2009), this approach works best when spatial treatments are applied at field resolution levels 1, 2, and 3. Pixel sizes decrease with closer closeness; they frequently measure millimeters or less. This function is useful for analyzing photos that capture details unique to a species, such as texture, shape, and arrangement of plants. Images from ground-based camera systems and the image processing techniques that follow help to differentiate individual weed plants from agricultural plants because their spatial resolution is less than 1 mm (Thorp and Tian, 2004). Because the sprayer control system has to do a lot more work to find and identify weeds and then decide which course of action to take in real time, data needs to be processed very quickly in order to keep the sprayer moving at an acceptable speed. In contrast to the aerial mapping method, no further work or infrastructure is needed.

2. **Aerial-Based Remote Sensing (ARS) System:** There are two essential requirements for airborne remote sensing, which can be carried out from a satellite platform or an airplane. First, weeds and the surrounding soil and plant canopy need to differ noticeably in terms of spectral reflectance or texture. The second need is that in order to identify weed plants, the remote sensing device needs to have sufficient spectral and spatial resolution. When it comes to detecting well-defined weed patches that are dense, consistent, and have unique spectral properties—that is, weed patches bigger than 1×1 m—airborne remote sensing techniques work effectively. As such, this method works well for treating entire fields as well as weed patches or subfields that have weed plant clusters in them. However, a significant drawback of airborne remote sensing is the potential difficulty in obtaining

data when required, particularly if unfavorable weather conditions occur during the passage of the satellite or aircraft. In such instances, data acquisition may experience delays lasting for days or even weeks, as discussed by Christensen et al. (2009). Singh et al. (2020) examined recent research that investigated the possibilities of Unmanned Aircraft Systems (UAS) platforms and remote sensing instruments for precision weed management and weed monitoring. Despite the investigation of various weed sensing techniques and some progress in the development of weed mapping and control software tailored for precision agricultural practices in recent years, the adoption of site-specific weed management remains limited among farmers. To date, no technique has evolved into a commercial product. The economic and technological constraints associated with site-specific weed management may currently hinder its widespread implementation. However, as research advances and technology undergoes refinement, leading to cost reductions, the prospects for site-specific weed management at the farm level are expected to significantly expand.

VI. ROBOTIC TECHNOLOGY

A different strategy for site-specific weed treatment has evolved recently with the advent of robotic technologies. Precision agriculture is a progressing field that includes weed management. It is similar to manual operations like hand hoeing or backpack spot spraying, but it does not require human interaction (Osten and Crook, 2016). An autonomous, self-guiding platform with a variety of weed sensing modules is the centerpiece of an agricultural weeding robot, which consists of both hardware and software components. According to Osten and Crook (2016), these devices in turn activate a variety of weeding instruments, such as tillage tools, spray nozzles, and microwave units. Agricultural robotic systems are engineered to be highly adaptable, capable of performing a multitude of tasks like planting, fertilizing, misting, surveying, tallying, and perceiving. They also provide diverse weed control options, such as chemical, mechanical, electrical, and thermal techniques, and are built to last, reducing the necessity for tractor-dependent operations (Perez and Gonzalez, 2014). They help to lessen the need for labor and soil compaction. Globally, a broad variety of robotic devices and systems are currently in development, such as AgBot, Swarmbots, RIPPA, Ladybird, EcoRobot, Robocrop, IC-Cultivator, Robovator Hoeing Robot, and Thermal Hoeing Robot (Rao, 2018).

1. **Hortibot:** With its navigational platform fitted with many weed management equipment, the semi-autonomous Hortibot robot can mechanically pull weeds or provide precise spraying. It can navigate through the harvest thanks to a vision-based navigation system that combines downward-focused cameras. Furthermore, it is equipped with a computer and GPS technology to locate weeds and plants precisely. This versatile robot has the capability to manually pluck weeds, apply sprays, or employ methods such as flames or lasers for weed removal. When using herbicides, it precisely targets the area directly above the weeds. This environmentally-friendly robot, weighing between 200 to 300 kg, possesses the ability to identify approximately 25 different weed types (source: https://www.zdnet.com/article/hortibot-a-weed-removing-robot/). Further enhancements could potentially expand its weed recognition capabilities.

2. **Robocrop:** The Robocrop, created in the UK by Tillet and Hague Technology Ltd., is the first robotic weeding system available for purchase. It works by using a forward-facing

camera to identify the crop plants and a set of rotating disc blades mounted on an off-center shaft to cultivate the area surrounding the plants in the row. A digital video camera is used by the precision guidance system for inter-row navigation to take pictures of the crops in the row. These photos are then analyzed to pinpoint the exact locations of each plant. The hoe is then maneuvered laterally and the In-Row Weeder disc is synchronized with its operation thanks to this information. The rotation of the disc is synchronized with forward motion and is dependent on plant position information obtained from the image camera. With Robocrop, you can remove up to three plants per row in an efficient manner because of a program that continuously modifies the disc's spinning speed to account for differences in plant spacing. 3.2 hectares may be covered in an hour by a system that is 6 meters wide, travels at 5.4 km/h, and has a plant spacing of 50 cm. Although this robotic device can cultivate more than 98% of the area, it may have difficulties in rows with crop plants that are closely spaced or densely packed, as well as in circumstances where the size of weeds and crop plants are similar (source: Adapted from https://www.zdnet.com/article/hortibot-a-weed-removing-robot/).

2. **IC cultivator:** The IC Cultivator, which was created in the Netherlands in 2012 and released onto the European market in 2013, uses hooded cameras that are fitted with artificial LED (light-emitting diode) lighting for every planted row in order to identify different crop plants. A series of cultivator knives, which are inserted into the seed line around the crop plants to efficiently remove weeds, are activated by a pneumatic cylinder while the machine progresses. Both the plants and the row pattern are identified by the camera. This hydraulically-powered modular hoe blade has a width adjustment range of 1.5 to 6.0 meters, allowing it to hoe 3-5 plants per second at a pace of 3–4 km/h.

3. **Robovator hoeing robot:** The Robovator Hoeing Robot was created in Denmark. It operates similarly to the IC-Cultivator in terms of concept and construction, but it lacks the hooded design and depends on artificial lighting to maintain consistent image quality. This robot has a mechanical tool that is powered by hydraulics and a specialized plant detecting camera that is positioned above each row. When a crop plant is spotted, the "intelligent" weeding instruments retreat, yet they normally stay in the row. Every parallelogram has specialized plant detecting cameras installed on it that continuously watch the plants that pass by. The hydraulic tool is relocated out of the row for a predetermined amount of time after the computer detects the presence of a crop plant. The tool is placed back into the row after the crop plant has passed. The tool stays in the row if there is a space between the plants and one or more of the plants are missing. When the tractor veers off course, the automated lateral control makes sure that the apparatus stays in the exact spot.

4. **Thermal Hoeing Robot:** The Robovator vision system is utilized by the Danish-made thermal hoeing robot to identify crop plants. This robot features a set of plasma jets positioned toward the crop row, emitting flames to eliminate weeds. To ensure effective weed control, multiple jets are employed to provide an ample amount of heat for weed eradication. The robot operates at speeds ranging from 1 to 6 km/h.

5. **EcoRobot:** Created in Switzerland by Ecorobotix, the EcoRobot represents a groundbreaking, compact robot designed for both environmentally-friendly and cost-effective weeding in row crops. This robot executes weed removal by utilizing an

advanced vision system that identifies weeds and a swift robotic arm capable of eliminating them through spot spraying or a spinning disk. Its lightweight design ensures easy transportation, and it operates on solar power, allowing it to perform weed control with a remarkable 95% efficacy over several days.

6. **Ladybird:** Ladybird, so named because of its beetle-like look (Blucher, 2014), was developed at the University of Sydney's Australian Centre for Field Robotics (ACFR). This cutting-edge device was created to be used on commercial vegetable farms, where it can do a variety of autonomous functions like mapping, surveillance, classification, weed management, and the detection of different veggies. With its omnidirectional capabilities and array of sensors, which includes stereo cameras, hyper-spectral cameras, and lasers, the solar-electric driven ground vehicle can detect the growth of vegetables, the presence of weeds, and possible animal pests. Furthermore, Ladybird has a robotic arm intended for pulling weeds that may be used for self-sufficient harvesting (Hollick, 2014).

7. **Bonirob:** Approximately the size of a compact car, Bonirob was created by Deepfield Robotics, a division of Bosch in Germany. It uses satellite navigation, LIDAR (Light Detection and Ranging)-based positioning, and video to navigate fields, guaranteeing that it is aware of its exact location to the nearest centimeter. Pulsed laser light is used in LIDAR, a distant sensing method, to determine varying distances to Earth. Bonirob possesses the capability to differentiate between weeds and crops by employing machine learning algorithms that analyze various factors, including leaf color, shape, and size, and it can do this by comparing them to images. To mechanically manage weeds, the robot is equipped with a rod that swiftly and effectively drives them into the ground (Anonymous, 2015).

   Bonirob employs a punching mechanism, similar to a swift jab, rather than relying on herbicides for weed control. The punching approach offered by Bonirob is regarded as superior because it involves a single action, unlike the process of manually pulling out a weed, which requires grasping and subsequent handling. The punching or ramming action is executed rapidly, taking just 0.01 seconds, making it a task ideally suited for a robot. Additionally, the robot can operate continuously for 24 hours without requiring refueling, thanks to its onboard generator.

8. **AgriBot:** Agribot, developed by Queensland University of Technology in Australia, is a compact autonomous vehicle, similar in size to a golf buggy. The newer iteration, AgriBot II, offers assistance to farmers by handling tasks such as seeding, fertilizer application, and weed control (Bryant, 2014). It relies on an array of sensors, sophisticated software, and other electronic components to navigate fields accurately while detecting, precisely categorizing, and eliminating weeds. Weed eradication is achieved with great precision through the application of herbicides, minimizing wastage, or through mechanical hoeing. Mechanical removal is employed for weed species that have developed resistance to herbicides. Powered by solar energy, the Weed Terminator, Agribot II, has the potential to reduce crop weeding costs by approximately 90%.

9. **RIPPA:** RIPPA (Robot for Intelligent Perception and Precision Application) is an ongoing project of Sydney University's Australian Center for Field Robotics. This self-driving car is battery- and solar-powered, and it can map the crop area and detect weeds

using sensors. It has an advanced applicator that can quickly and precisely apply herbicides at the appropriate dosage. According to current specifications, this machine can spray fertilizer and weeds, estimate crop production, and run continuously for up to 21 hours in a single trip

VII. FUTURE LINE OF RESEARCH FOR ADOPTION OF PRECISION WEED MANAGEMENT TECHNIQUES

The upcoming generation of weed scientists will confront complex challenges as they strive to devise and apply optimal weed management strategies. While herbicides will persist as a tool, their usage may become more restricted. Thus, maintaining thorough knowledge in the chemistry, physiology, and technology of herbicides is essential. The growing issue of weed resistance to pesticides will make weed biology more and more important. Herbicide-resistant transgenic crops will continue to be developed, even though acceptance will take time. The field of precision weed management, currently in its early stages, is poised for growth. In light of these evolving demands, weed scientists must cultivate expertise in the following areas:

- The fundamental mechanisms that govern interactions between plants.
- Modeling of plant populations.
- Advancements in weed genomics (genome sequencing) and metabolomics (analysis of metabolomes), as highlighted by Rao in 2018, along with high-throughput screening techniques for herbicides.
- The evolutionary processes leading to weed resistance against herbicides, particularly non-target resistance, as well as the factors contributing to their infestation and widespread distribution.
- Strategies aimed at enhancing crop competitiveness against weeds, encompassing modifications in crop growth responses and exploring allelopathic effects, among other approaches.
- The use of robotics technology to the field of precision weed management and automated identification of weeds and invasive plant species through the use of remote sensing, geographic information systems, and machine vision.
- Precision weed control technology, which include new approaches as well as chemical and physical advancements.
- Engaging in partnerships with software experts and engineers to create advanced ground-based and aerial-based remote sensing systems, aiming for enhancements and innovations.

To bring about a fundamental change in weed management, it is imperative to provide training and engage weed scientists in these emerging technologies (Rao, 2021).

VIII. ECONOMIC ASPECTS, COMMERCIAL ADAPTATION AND ECOLOGICAL BENEFITS

Chemical crop protection is becoming less and less accepted in society. More people now see pesticides as contaminants that may affect food safety and devastate ecosystems. Legislative initiatives and political activities reflect this growing concern. Due to their poor ecological profiles and other environmental difficulties, the use of herbicides has already been restricted and is probably going to be further restricted (European Commission, 2019). The European Commission (2020) aims to promote the adoption of safer alternative ways for pest management while reducing the overall use and risk associated with chemical pesticides by 50% by 2030. These objectives are defined in the Green Deal and Farm to Fork policies. In order to achieve these goals and comply with upcoming environmental policy measures, farmers will need to adopt novel technologies, such as site-specific weed management (SSWM).

Growing consumer interest in organic foods is another factor projected to fuel demand for environmentally friendly weed control techniques. Approximately 14 million hectares of organic farming were practiced in the EU-27 in 2019, which represents 8.5% of the total cultivated land in those nations. Interestingly, the area used for organic farming increased by 46% between 2012 and 2019 (Eurostat, 2021). The ambitious target of 25% organic farming area by 2030 has been set by the new Action Plan for the growth of organic production in the EU (European Commission, 2020).

The use of robotics and other precision agriculture technologies is widely acknowledged to have the potential to increase farm profitability and production (Bongiovanni and Lowenberg-DeBoer, 2004). However, the implementation of Site-Specific Weed Management (SSWM) is a more complex issue. The implementation of SSWM technologies can vary and depends on various environmental and economic factors. One critical question revolves around which farming operations should be replaced by these new technologies. Productivity can surely be increased by using robotic weeding platforms in place of hand weeding (Perez-Ruiz et al., 2014; Sorensen et al., 2005). While manual weeding is still used sparingly in developed nations, the burgeoning organic farming industry offers this technology a significant window of opportunity. However, because determining profitability can be difficult, farmers are still hesitant to invest in precision weed management systems. A number of aspects need to be taken into account while introducing robotics, including the cost of purchasing, yearly usage, field capacity, and weeding effectiveness. Some factors need to be proven by long-term operation, such as the total lifespan and maintenance expenses of SSWM. Farmers have reasonable concerns about new activities that will demand increased technical and IT knowledge, therefore adopting SSWM technology may not be hampered just by financial considerations (Balafoutis et al., 2020).

A 50% decrease in herbicide costs was noted by Gerhards and Oebel (2006) in relation to site-specific herbicide application. But the real savings amount depends on how densely and densely-packed weed populations are. However, low levels of weed infestation and whether or not the time and resources needed for weed detection and variable herbicide application result in a material increase in treatment costs are necessary for this technique to be viable (Swinton, 2005). Simulations were used by Andujar et al. (2013) to manage S. halepense in maize crops. When weed infestation was less than 19% of the field, they discovered that site-specific weed management was the most successful tactic. Robotic weeding can reduce labor expenses in organic farming, allowing farmers to grow more labor-intensive crops or even more profitable crop cycles. There might be potential to sell agricultural products for more money if conventional farms use Site-Specific Weed Management (SSWM) (Lowenberg-DeBoer et al., 2020).

The environmental benefits of Site-Specific Weed Management (SSWM) technologies, especially the significant reduction in pesticide usage, are anticipated to be the primary driving force behind their integration into traditional farming operations. Adoption of this technique will also be influenced by economic factors, such as reducing pesticide costs and limiting yield losses resulting from populations of herbicide-resistant weeds. Nevertheless, farmers frequently continue to favor chemical weed management due to its great effectiveness and affordable price (Swinton, 2005). Farmers will be more receptive to SSWM technologies if they can offer more compelling competitive benefits. Examples of such advantages include raising the price of produce with minimal residue or offering direct and indirect subsidies for the purchase and use of precision farming equipment. To encourage farmers to adopt more ecologically friendly weed control techniques, agro-environmental policies might be used. However, according to Barnes et al. (2019), there are currently no explicit legal requirements in place in the EU for the implementation of precision agriculture technologies.

The possible increase in weed biodiversity that can be attained by using a more focused and targeted weed control strategy that only targets unwanted weed species is another benefit. This technique makes it possible to identify, locate, and exclude rare, advantageous, or endangered species from medical interventions. Newly imported invasive species, on the other hand, can be eliminated before they create a persistent seedbank. Using Site-Specific Weed Management (SSWM) can help promote the use of more varied crop rotation strategies. Many crops that growers currently overlook because of the scarcity of weed management solutions may become more desirable. By consuming less fuel and carbon and avoiding soil compaction, robotic weeding machines also provide an additional environmental benefit. This is especially true when employing tiny robotic weeding units.

IX. CONCLUSIONS

With the global population increasing and the corresponding demand for food production, there is a pressing requirement to enhance the management of the world's agricultural resources while mitigating adverse environmental impacts. From an agronomic standpoint, weeds are viewed as a significant threat, leading to reduced agricultural efficiency and yield losses. Nevertheless, when viewed ecologically, they can also be seen as valuable indicators of biodiversity within the agricultural ecosystem, offering ecological services as integral components of the agroecosystem. Weed management encompasses various methods; however, relying solely on one control method is insufficient for sustainable, long-term weed management and often leads to the development of resistance. Consequently, there is a critical need to integrate diverse weed control strategies within a comprehensive approach.

The utilization of herbicides disrupts ecological equilibrium, potentially leading to the development of resistance in certain species exposed to prolonged chemical application.

Equally significant are the environmental issues stemming from herbicide use, posing a substantial threat to the health and well-being of both animals and humans.

Hence, the sustainable management of agricultural systems, particularly in relation to weed control, remains a critical concern for the well-being and future of humanity. Alongside integrated management approaches, the advancement of precision technologies for weed control holds significant potential to enhance sustainability and agricultural productivity within the context of smart agriculture. To achieve this, it is advisable to foster more effective collaboration between researchers and farmers, emphasizing the integration of ecological and technological principles into weed management decision-making processes.

REFERENCES

[1] Andujar, D., Ribeiro, A., Fernández-Quintanilla, C. & Dorado, J. 2013. Herbicide savings and economic benefits of several strategies to control *Sorghum halepense* in maize crops. *Crop Protection*. 50:17–23.

[2] Anonymous. 2015. Intelligence for the fields: Bosch robot gets rid of weeds automatically and without herbicides. Bosch Deepfield Robotics I News I October 8, 2015 [*URLhttp:// www. deepfieldrobotics.com/en/News-Detail_151008. html*].

[3] Anonymous. 2017. PAN—Pesticide Action Network Europe. Alternative Methods in Weed Managment to Glyphosate; Intergrated Weed Management. Pesticide Action Network Europe: Brussels,

[4] Belgium, 2017. Available online: *https://www.pan-europe.info/sites/pan-europe. info/files/Report_Alternatives%20to%20Glyphosate_July_2018*.

[5] Balafoutis, A.T., Van Evert, F.K. and Fountas, S. 2020. Smart farming technology trends: economic and environmental effects, labour impact, and adoption readiness. *Agronomy*. 10: 743.

[6] Barnes, A.P., Soto, I., Eory, V., Beck, B., Balafoutis, A.T., Sanchez, B. *et al*. 2019. Influencing factors and incentives on the intention to adopt precision agricultural technologies within arable farming systems. *Environmental Science and Policy*. 93: 66–74.

[7] Beckie, H.J., Ashworth, M.B. and Flower, K.C. 2019. Herbicide resistance management: Recent developments and trends. *Plants*. 8: 161; *doi:10.3390/plants8060161*.

[8] Blucher, A. 2014. World first farm robot set to revolutionise vegetable farming. ABC Rural News webpage. [*URL http://www.abc.net. au/news/2014-06-25/farm- robotics- university-of-sydneyvegetable-farming/5550076*].

[9] Bongiovanni, R. and Lowenberg-DeBoer, J. 2004. Precision agriculture and sustainability. *Precision Agriculture*. 5: 359–387.

[10] Brown, R. and Noble, S. 2005. Site-specific weed management: Sensing requirements- what do we need to see. *Weed Science*. 53(2): 252–258.

[11] Bryant, S. 2014. Could weed-zapping Daleks be the new farmer's friend, with robots roaming crops? ABC Rural News webpage. [*URL http://www.abc.net.au/news/2014-07-30/ nrnweedzapping-daleks/5633014*].

[12] Buhler, D.D., Liebman, M. and Obrycki, J. J. 2000. Theoretical and practical challenges to an IPM approach to weed management. *Weed Science*. 48:274- 2280.

[13] Chauhan, B.S. 2020. Grand Challenges in Weed Management. Frontier Agronomy. 1:3.

[14] *doi: 10.3389/fagro.2019.00003*.

[15] Christensen, S., Sogaard, H.T., Kudsk, P., Norremark, M., Lund, I., Nadimi, E.S. and Jorgensen, R. 2009. Site-specific weed technologies. *Weed Research*. 49: 233– 241.

[16] Dabney, S.M., Delgado, A. and Reeves, D.W. 2001. Using winter cover crops to improve soil and water quality. *Commun. Soil Sci. Plant Anal*. 32, 1221.

[17] David, L. and Brown, R.B. 2001. Remote-sensing and mapping of weeds in crops.

[18] *Journal of Agricultural Engineering Research*. 78: 117–125.

[19] European Commission. 2019. Commission Implementing Regulation (EU) 2019/1100 of 27 June 2019 concerning the non-renewal of approval of the active substance desmedipham, in accordance with Regulation (EC) No 1107/2009 of the European Parliament and of the Council concerning the placing of plant protection products on the market, and amending the Annex to Commission Implementing Regulation (EU) No 540/2011.

[20] European Commission. 2020. Communication from the Commission to the European Parliament, the

Council, the European economic and social committee and the Committee of the regions. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food sys- tem. 20.5.2020.

[21] Eurostat. 2021. Organic farming statistics. Available at: *https://ec.europa. eu/eurostat/statistics-explained/index.php/Organic_farming_statistics*.

[22] Fernandez-Quintanilla, C., Pena, J.M., Andujar, D., Dorado, J., Ribeiroand, A. and Lopez-Granados, F. 2018. Is the current state of the art of weed monitoring suitable for site-specific weed management in arable crops? *Weed Research*. 58: 259– 272.

[23] Gerhards, R. and Oebel, H. 2006. Practical experiences with a system for site-specific weed control in arable crops using real-time image analysis and GPS-controlled patch spraying. *Weed Research*. 46: 185–193.

[24] Gerhards, R., Sökefeld, M., Nabout, A., Therburg, R.D. and Kühbauch, W. 2002. Online weed control using digital image analysis. *Journal of Plant Diseases and Protection*. 18: 421–427.

[25] Gnanavel, I. 2015. Eco-Friendly Weed Control Options for Sustainable Agriculture. *Sci.Int.* 3: 37–47.

[26] Hammermeister, A. 2016. Organic weed management in perennial fruits. *Sci. Hortic*.208: 28–42.

[27] Hamouz, P., Hamouzova, K., Holec, J. and Tyser, L. 2013. Impact of site-specific weed management on herbicide savings and winter wheat yield. *Plant, Soil and Environment.* 59(3): 101– 107.

[28] Hartzler, R. and Buhler, D. 2007. Management of agricultural weeds. Ecologically Based Integrated Pest Management. In Opender KoulGerrit and W. Cuperus; CABI: Wallingford, UK, 2007; pp. 37–51. ISBN 9781845931636.

[29] Hollick, V. 2014. Ladybird developer awarded research of the year. News page, 24 June 2014. The University of Sydney website. [*URL http:// sydney.edu.au/news/84.html? newsstoryid= 13686*].

[30] ISAAA. 2019. Global Status of Commercialized Biotech/GM Crops in 2019. ISAAA Brief No. 55. ISAAA: Ithaca, NY.

[31] Lancaster, S.R. 2021. Chemical Weed Control for Field Crops, Pastures, Rangeland, and Noncropland; Kansas State University: Manhattan, KS, USA, 2021; p. 148. Available online:

[32] *https://www.bookstore.ksre.ksu.edu/pubs/CHEMWEEDGUIDE*.

[33] Lowenberg-DeBoer, J., Huang, I.Y., Grigoriadis, V. and Blackmore, S. 2020. Economics of robots and automation in field crop production. *Precision Agriculture*. 21: 278–299.

[34] Mia, M.J., Massetani, F., Murri, G. and Neri, D. 2020. Sustainable alternatives to chemicals for weed control in the orchard—A Review. *Hortic. Sci*. 47: 1–12

[35] Monteiro, A. and Santos, S. 2022. Sustainable Approach to Weed Management: The Role of Precision Weed Management. *Agronomy.* 12: 118. *https://doi.org/10.3390/agronomy12010118.*

[36] MacLaren, C., Storkey, J. and Menegat, A. 2020. An ecological future for weed science to sustain crop production and the environment. A review. *Agron. Sustain. Dev*. 40: 24.

[37] Nukala, R., Panduru, K., Shields, A., Riordan, D., Doody, P. and Walsh, J. 2016. Internet of things: A review from farm to fork. 27th Irish Signals and Systems Conference (ISSC) (2016), pp. 1-6, DOI-10.1109/ISSC.2016.7528456.

[38] Osten, W. and Cook, N. 2016. A review of technologies that can be enabled byrobotics to improve weed control in Australian Cotton Farming Systems. Cotton Research and Development Corporation, Swarm Farm Robotics, Gindie, Queensland.

[39] Pannacci, E., Lattanzi, B. and Tei, F. 2017. Non-chemical weed management strategies in minor crops: A review. *Crop. Prot*. 96: 44–58.

[40] Ribas, P. and Matsumura, A. 2009. The chemistry of pesticides: Impact on health and the environment. *Rev. Lib.*10: 149–158.

[41] Peera, P., Debnath, S. and Maitra, S. 2020. Mulching: Materials, Advantages and Crop Production. In Protected Cultivation and Smart Agriculture; New Delhi Publishers: New Delhi, India, 2020; pp. 55–66.

[42] Pérez-Ruíz, M., Slaughter, D.C., Fathallah, F.A., Gliever, C.J. and Miller, B.J. 2014. Co- robotic intra-row weed control system. *Biosystems Engineering*. 126: 45–55.

[43] Popay, I. and Field, R. 1996. Grazing Animals as Weed Control Agents. *Weed Technology*. 3:12-20.

[44] Perez, T. and Gonzalez, F. 2014. Agricultural robotics an outlook into a new generation of tools for site specific crop and weed management. pp. 52–59. In: Proceedings 17th Precision Agriculture Symposium of Australasia.

[45] Rao, V.S. 2018. Principles of Weed Science (Third Edition). CBS Publishers and Distributors Pvt. Ltd. New Delhi, India.

[46] Rao, V.S. 2021. Precision weed management-A means of boosting Agricultural productivity. *Indian Journal of Weed Science*. 53(3):209-215.

[47] Rueda-Ayala, V., Rasmussen, J. and Gerhards, R. 2020. Mechanical Weed Control. In Precision Crop Protection-the Challenge and Use of Heterogeneity; Oerke, E.C., Gerhards, R., Menz, G., Sikora, R., Eds.; Springer: Dordrecht, The Netherlands, 2020.
[48] Santos Valle, S. and Kienzle, J. 2020. Agriculture 4.0—Agricultural Robotics and Automated Equipment for Sustainable Crop Production. In Integrated Crop Management; FAO: Rome, Italy, 2020; Volume 24, Available online:
[49] http://www.fao.org/3/cb2186en/CB218 6EN.
[50] Scavo, A. and Mauromicale, G. 2020. Integrated Weed Management in Herbaceous Field Crops. *Agronomy*. 10: 466.
[51] Sims, B., Corsi, S., Gbehounou, G., Kienzle, J., Taguchi, M. and Friedrich, T. 2018. Sustainable Weed Management for Conservation Agriculture: Options for Smallholder Farmers. *Agriculture*. 8:118.
[52] Singh, V., Rana, A., Bishop, M., Filippi, A.M., Cope, D., Rajan, N. and Bagavathiannan,
[53] M. 2020. Chapter Three - Unmanned aircraft systems for precision weed detection and management: Prospects and challenges. *Advances in Agronomy*.159: 93– 134.
[54] Sorensen, C.G., Madsen, N.A. and Jacobsen, B.H. 2005. Organic farming scenarios: operational analysis and costs of implementing innovative technologies. *Biosystems Engineering*. 91: 127–137.
[55] Sundmaeker, H., Verdouw, C., Wolfert, S. and Prez Freire, V. 2020. Internet of food and farm Digitising the Industry - Internet of Things Connecting Physical, Digital and Virtual Worlds, 2 (2016), pp. 129-151.Swinton, S.M. 2005. Economics of site-specific weed management. *Weed Science*. 53: 259–263.
[56] Thorp, K.R. and Tian, L.F. 2004. A review on remote sensing of weeds in agriculture.
[57] *Precision Agriculture.* 5: 477–508.
[58] Wang, A.W., Wen, Z. and Wei, X. 2019. A review on weed detection using ground-based machine vision and image processing techniques. *Computers and Electronics in Agriculture.* 158: 226–240.
[59] Young, S., Pierce, J. 2014. Automation: The Future of Weed Control in Cropping Systems; Springer: Berlin/Heidelberg, Germany, 2014; pp. 249–259.